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Vibrations Generated by Rolling Element Bearings having Multiple Local Defects on Races

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Abstract

The vibrations generated by deep groove ball bearings having multiple defects on races have been studied in this paper. The vibrations are analysed in both time and frequency domains. The equations for time delay between two or more successive impulses have been derived and validated with simulated and experimental results. The relationships between amplitudes of frequencies for impulse train, delayed impulse train and combination of two impulse trains have been established. Frequency spectra for single and two defects on either race of deep groove ball bearings are compared. No additional frequencies due to time delay between successive impulses are observed in case of multiple defects. The frequency spectra do not provide any information about number of defects; however this information is found in time domain analysis.

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Keywords: Rolling element bearings; vibrations; phase angles; multiple defects

1. Introduction

In a majority of machines, deep groove ball bearings can be found to be carrying the load efficiently. Generally local defects (such as spalls, pits, cracks etc.) appearing on mating components of bearings are generated due to fatigue. If such defects are not detected at an early stage, then through passage of time these may lead to failure of the bearings/machines. This may cause severe safety problems and economical losses. In industries, vibration monitoring is commonly done to check the health of bearings in terms of detection of the defects before reaching the critical stage. The vibration spectra generated due to presence of local defects have been analysed and identified by various researchers in time and frequency domains.

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Most of the theoretical and experimental studies [1-2] reported on vibration generation in rolling element bearings consider single local defect. However, a few studies [3-5] have incorporated two local defects in vibration analysis of rolling element bearings. McFadden and Smith [3] have studied vibration response of deep groove ball bearings considering two point defects on inner race using a simple mathematical model. The authors have reported that the frequencies components from defects are independent of defect position, but the phase angles of these components are related to the position of the defect. Igarashi and Kato [4] have derived the equations for the time delay between two defects on inner race/outer race. Patel et al. [5] have modelled the multiple defects by considering the masses of rolling elements, shaft and housing. The authors have validated their dynamic model of deep groove ball bearing incorporating two defects on inner and outer races with experimental results.

Literature review reveals dearth of the theoretical and experimental studies pertaining to vibrations generated by rolling element bearings having multiple defects on bearing elements. Moreover, the authors of this paper have noticed relatively lack of clarity in understanding the vibrations of rolling element bearings in the presence of multiple defects. Therefore, the objective of this paper is to provide better understanding the vibrations responses generated due to the presence of multiple defects on the inner/outer race of deep groove ball bearings performing theoretical and experimental investigations. The time delays between two successive impulses have been derived and discussed. The dynamic model developed by Patel et al. [5] has been used for simulation and validation of computed time delays. Moreover, the time delay between two successive impulses is also compared with experimental results of the bearings having defects on outer race. The frequency spectra of experimental data for a bearing having single defect and two defects on either race have been compared. The properties of Discrete Fourier Transform (DFT) have also been discussed in depth. The present study may be useful for practising engineers/researchers in industries for understanding the vibrations generated by multiple defects on the bearing races.

2. Time domain analysis

The vibration energy of the bearing signal changes due to the interaction of the local defects with the rolling elements of the bearing. The change in the vibration energy in the form of peaks can be noticed in the time domain signal captured from the defective bearing. In case of multiple defects on the races, the rolling elements strike the defects after certain interval of time and accordingly peaks (impulses) are produced. The time delay(τ) between two successive impulses depends on the angular position of the defects on races and also on ball pass frequencies of single defect. The ball pass frequency for outer race (BPFO) is given by $\left[BPFO, f_{0ut} = (N_b/2)*(N_s/60)*(1 - d/D)\right]$. The ball pass frequency for inner race (BPFI) is given by: $\left[BPFI, f_{in} = (N_b/2)*(N_s/60)*(1 + d/D)\right]$. Where, D is pitch diameter, d is ball diameter, N_b is number of balls and N_s is shaft rotations speed. The fundamental equations of motions proposed by Patel et al. [5] have been used for simulation purpose.

2.1. Defects on outer race

In the present study three defects, 'A', 'B' and 'C' have been considered on the outer race of the bearing, the different position of defects are graphically represented in Fig.1 (a-d). The angular difference between defect 'A' and defect 'B' is 'ϕ_{def1}', while, the angular difference between defect 'A' and defect 'C' is 'ϕ_{def2}'. In the present study four different possibilities of the defects locations are considered as below:

(a) $\phi_{def1} < \theta$ and $\phi_{def2} < \theta$; (b) $\phi_{def1} < \theta$ and $\phi_{def2} > \theta$; (c) $\phi_{def2} = \theta$ or $\phi_{def1} < \theta$; (d) $\phi_{def1} > \theta$ and $\phi_{def2} > \theta$.

When three defects are lying between two successive balls (When $\phi_{def1} < \theta$ and $\phi_{def2} < \theta$), the same ball strikes the defects 'A', 'B' and 'C' at time 't_1', 't_2' and 't_3' respectively. The time delay between two successive strikes i.e. between 't_1' and 't_2' is 'τ_1' while between 't_2' and 't_3' is 'τ_2'. These time delays are expressed by the following equations:

$$\tau_1 = t_2 - t_1 = \frac{\varphi_{def\,1}}{\theta f_{out}} \quad \text{and} \quad \tau_2 = t_3 - t_2 = \frac{\varphi_{def\,2} - \varphi_{def\,1}}{\theta f_{out}} \tag{1}$$

In this case two defects 'A' and 'B' are located between two successive balls while the third defect 'C' is located between next two successive balls (When $\phi_{def1} < \theta$ *and* $\phi_{def2} > \theta$). Based on the angular difference this is further divided into two possibilities as discussed below:

When $\phi_{def\,2} - \theta > \phi_{def\,1}$, same ball (ball number 1) strikes defect 'A' at time 't_1' and strikes defect 'B' at time 't_2', after these strikes the next ball (ball number 2) strikes the defect 'C' at time 't_3'. Mathematically, the time delays in strikes are written as follows:

$$\tau_1 = t_2 - t_1 = \frac{\varphi_{def\,1}}{\theta f_{out}} \text{ and } \tau_2 = t_3 - t_2 = \frac{\varphi_{def\,2} - \theta - \varphi_{def1}}{\theta f_{out}} \tag{2}$$

When $\phi_{def2} - \theta < \phi_{def1}$, ball number 1 strikes the defect 'A' at time 't_1' while ball number 2 strikes the defect 'C' at time 't_2' and further ball number 1 strikes defect 'B' at time 't_3'. The time delays in strikes are expressed by following relation:

$$\tau_1 = t_2 - t_1 = \frac{\varphi_{def\,2} - \theta}{\theta f_{out}} \text{ and } \tau_2 = t_3 - t_2 = \frac{\varphi_{def1} - \varphi_{def2} - \theta}{\theta f_{out}} \tag{3}$$

When $\phi_{def1} < \theta$ *and* $\phi_{def2} = \theta$, ball number 1 strikes defect 'A' at time 't_1' while the next successive ball (ball number 2) strikes the defect 'C' at time 't_2' (where, $t_2 = t_1$). After that, ball number 1 strikes the defect 'B' at time 't_3'. Therefore two strikes occur at the same time (i.e. $\tau_1 = 0$) and time delay, 'τ_2' between 't_3' and 't_2' is provided mathematically:

$$\tau_2 = t_3 - t_2 = \frac{\varphi_{def\,1}}{\theta f_{out}} \tag{4}$$

When angles 'ϕ_{def1}' and 'ϕ_{def2}' are more than the angle 'θ' (*When* $\phi_{def1} > \theta$ *and* $\phi_{def2} > \theta$) , ball number 1 strikes defect 'A' at time 't_1' while, ball number 2 strikes defects 'B' and 'C' at times 't_2' and 't_3' respectively.
The time delays between two successive strikes are given by the following equations.

$$\tau_1 = t_2 - t_1 = \frac{\varphi_{def\,1} - \theta}{\theta f_{out}} \text{ and } \tau_2 = t_3 - t_2 = \frac{\varphi_{def\,2} - \varphi_{def\,1}}{\theta f_{out}} \tag{5}$$

Thus, the generalised equation for time delays between two successive strike which occurs due to multiple defects on outer race and is expressed as follows:

$$\tau_n = t_{n+1} - t_n = \frac{\psi}{\theta f_{out}} \tag{6}$$

Where, 'ψ' is the difference between defect and the nearest ball in the direction of cage rotation and 'n' is an integer
(n < (Number of defects - 1)).

2.2. Vibration responses of bearing having multiple defects on outer race

The ball pass frequency of outer race (BPFO, f_{out}) for single defect at rotation speed of 1500 rpm is 76.67 Hz (bearing :SKF BB1 B420205). Figure 2 (a) shows the experimental time response measured on bearing housing. The angular difference between two defects is kept 30° ($\phi_{def} < \theta$), while the width of both rectangular defects are 2 mm. For more clarity, encircled part of Fig. 2(a) has been zoomed and shown in Fig. 2(b). The point 'A1' indicates the impulse generated when first defect strikes the ball at time t_1 =0.1152 sec, while point 'B1' indicates the impulse generated due to second defect strikes the same ball at time t_2 = 0.124 sec. Thus, the time delay (t_2- t_1) between two successive strikes is 8.8 X 10^{-3} sec, which is same as the time delay calculated by Eq. (6). The points 'A2' and 'B2' indicate strikes for the next successive ball.

Figure 3 (a) shows the simulated vibration response of bearing housing, for the bearing having two defects on outer race at angular difference, ϕ_{def} =45° (i.e. $\phi_{def} = \theta$) with defect size of 1 mm. From Fig. 3(a) it is observed that the time delay between two successive strikes is 0.01284 sec. This is same as 1/BPFO. Thus, the vibration response in time domain of the bearing having two defects on outer race at $\phi_{def} = \theta$ is the same as the vibration response (time) in case of single defect on outer race.

The numerical simulation was also performed for three defects on outer race of the bearing. Defect ‘A’ is at 0°, defect ‘B’ is at 15° and defect ‘C’ is at 75°. The ball number 1 strikes defect ‘A’ at time $t_1 = 0$ sec. and it strikes defect ‘B’ at $t_2 = 0.0044$ sec. (refer Fig. 3(b)). The angular position remaining between defect ‘C’ and ball number 2 is 15° and the computed time delay is 0.0044 sec. These two time delays ($\tau_1 = \tau_2 = 0.0044$ sec.) can be seen in Fig. 3(b). In addition to this, from Fig. 3(b) it is also observed that the amplitudes of successive peaks are decreasing. This variation in amplitude is expected due to the defect position with respect to load zone. The defect ‘A’ is under maximum load, while defect ‘B’ is little away from maximum load, while defect ‘C’ is at the end of load zone.

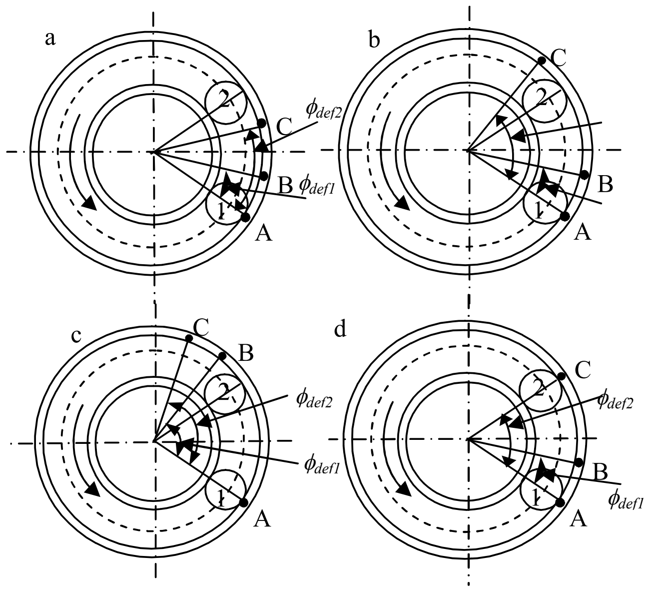

Fig. 1 Three defects on outer race
(a) $\phi_{def1} < \theta$ & $\phi_{def2} < \theta$ (b) $\phi_{def1} < \theta$ & $\phi_{def2} > \theta$
(c) $\phi_{def1} < \theta$ & $\phi_{def2} = \theta$ (d) $\phi_{def1} > \theta$ & $\phi_{def2} > \theta$

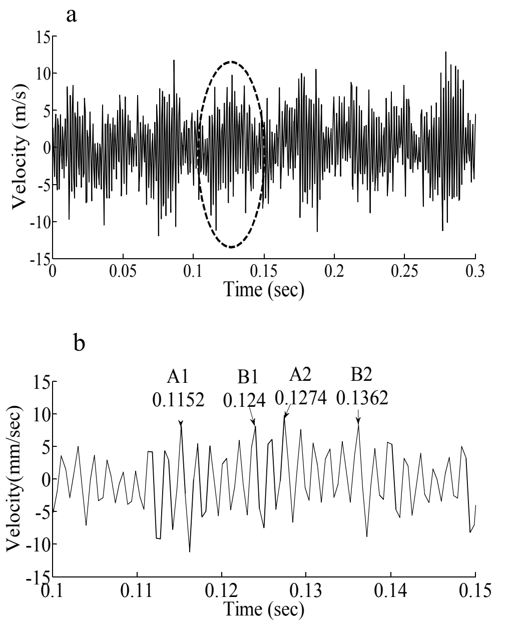

Fig. 2 Experimental vibration response of bearing having two defects on outer race (a) Vibrations measured on housing (b) Enlarged view of encircled zone (shaft rotation speed = 1500 rpm, $\phi_{def} = 30°$)

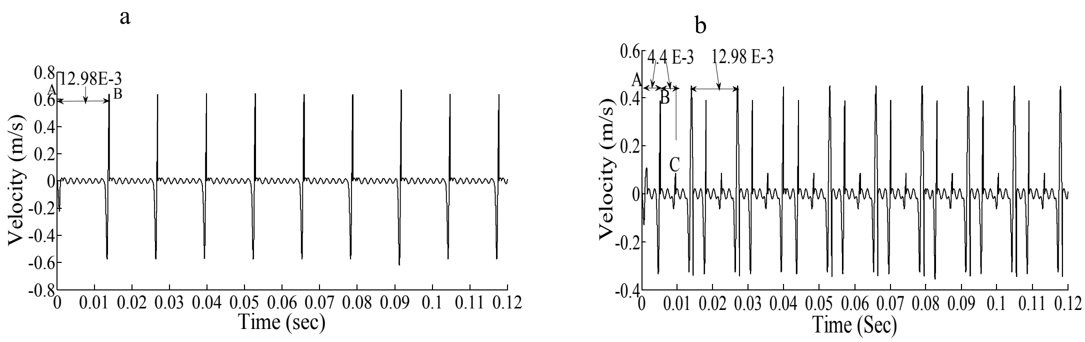

Fig. 3 Numerically simulated vibration response of bearing having multiple defects on outer race
(a) Two defect ($\phi_{def} = 45°$) (b) Three defect (ϕ_{def1}= 15°, ϕ_{def2}= 75°)

2.3. Defects on inner race

Inner race rotates with shaft speed as it is rigidly mounted on the shaft. Therefore, the defects on the inner race also rotate at shaft speed as opposed to outer race defects. Because of the rotation of the defects, the same ball does not strike the next defect but the successive ball strikes the next defect. From Fig. 4 it is observed that ball number 1 strikes defect 'A' at time 't_1' and ball number 2 strikes the defect 'B' at time 't_2'. In case of inner race defects the generalised equation for time delay between two strikes is expressed as follows:

$$\tau_n = t_{n+1} - t_n = \frac{\psi}{\theta f_{in}} \tag{7}$$

Where, 'ψ' is angle difference between defect, and nearest ball in direction of rotation of inner race, 'f_{in}' is ball pass frequency of inner race and 'n' is an integer.

2.4. Vibration responses of bearing having multiple defects on inner race

For the shaft rotational speed of 1500 rpm, the ball pass frequency of inner race (BPFI, f_{in}) is 122.95 Hz. The numerically simulated vibration response of the bearing having two defects on inner race of the bearing at angular difference of 30° is shown in Fig. 5(a). At time t = 0 sec defect 'A' is in contact with ball number 1 while, the angular difference between the defect 'B' and the successive ball is 15° (0.26 rad). The time delay between two successive impulses computed by Eq. 7 is 2.7 x10^{-3} sec, which can be seen in Fig 5(a).

For numerical simulation purpose three defects on inner race of the bearing have also been considered. The angular difference between defect 'A' and 'B' (ϕ_{def1}) is 15° and that between defect 'A' and defect 'C' (ϕ_{def2}) is 75°. The time delays computed by Eq. (7) for two successive impulses are $\tau_1 = \tau_2$ = 0.0027 sec. Figure 5(b) shows the simulated vibration response of the bearing housing having three defects on its inner race. In this case, ball number 1 strikes the defect 'A' at time t_1 = 0 sec. The angular difference between defect 'B' and ball number 2 is 30°, while between defect 'C' and ball number 3 is 15°. Due to the smaller angular difference, the ball number 3 strikes the defect 'C' at time delay $\tau_1 = t_2$ =0.0027 sec. The expected time delay between strikes of ball number 2 (defect 'B') and ball number 3 (defect 'C') is 0.0027 sec (ψ = 15°, τ_2 = 0.0027 sec). These time delays (τ_1, τ_2) are observed in Fig. 5(b). It is necessary to mention here that all peaks observed in Fig. 5 are due to the impact of balls but the variation in amplitudes is due to the time of occurrence of the impact. If the impact occurs in the load zone the amplitude of the impact is greater as compare to the amplitude of other impacts.

3. Frequency domain analysis

In condition monitoring of the bearings, frequency analysis of the time domain signal plays an important role. The rate of the repetition of impulses generated due to the interaction of the defects and rolling elements is observed in the frequency spectra of the time domain signal. For small defect size these impulses merge with other vibrations and it becomes difficult to identify them in time domain. In such case their repetition rate can easily be observed from frequency spectra. Although, along with frequency analysis some additional signal processing techniques help in noise removal [6,7].

The properties of Fourier transform like linearity of Fourier transform and shifting of sequence are important in understanding the Fourier transform of time delayed signal. In the present study, based on these properties of Fourier transform, the frequency spectrum expected due to the presence of multiple defects on bearing races has been investigated.

3.1 Linearity of Fourier transforms

If $f(n)$ and $g(n)$ are finite sequences while, $F(m)$ and $G(m)$ are their discrete Fourier transforms respectively, then the DFT of sequence $h(n) = af(n) + bg(n)$ is given as the same linear combination of the respective transforms, that is,

$$H(m) = aF(m) + bG(m) \tag{8}$$

Where *H(m)* is the DFT of the *h(n)*.

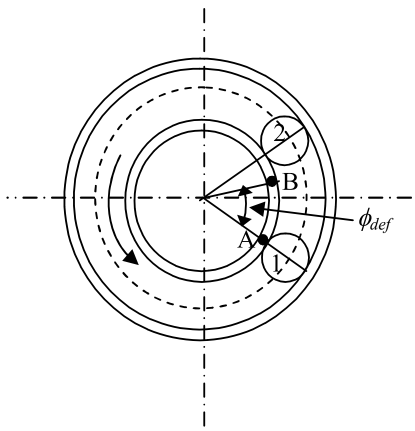

Fig. 4 Two defects on inner race

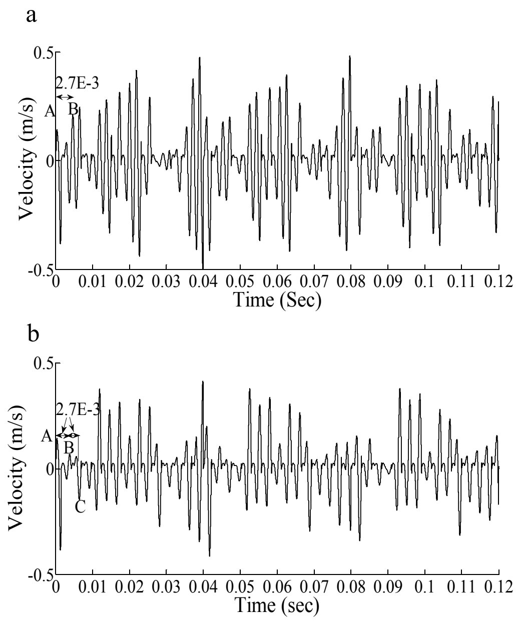

Fig. 5 Numerically simulated vibration response of bearing having multiple defects on inner race (a) Two defects (ϕ_{def} = 30°) (b) Three defects (ϕ_{def1}= 15°, ϕ_{def2}= 75°)

3.2 Shifting of sequence

There is an important property of the DFT known as the shifting theorem. It states that a shift in time of periodic *f(n)* input sequence manifests itself as a constant phase shift in angle associated with the DFT results. If the DFT of the Nth order sequence *f(n)* is *F(m)* , then the DFT of the shifted sequence *f(n-k)* which is shifted by *k* samples, is given by

$$F_{shifted}(m) = e^{j2\pi km/N} F(m) \tag{9}$$

From Eq. (9) it is clear that if the sequence is shifted by k samples, the DFT of output spectrum $F_{shifted}(m)$ is phase shifted by '2πkm/N' radians [8].

4. Frequency analysis of bearing

From the discussion in the section 3, it is clear that the frequencies expected in the frequency spectra of two or more local defects are the same as the frequencies present in the frequency spectra of single local defect. However, the amplitudes of the defect frequencies increase or decrease because of the phase shift resulted from time delay of impulses. In the present study magnitude of frequencies of single defect and two defects have been compared for experimental data.

The magnitudes for DFT have been measured for single defect and two defects. During experimentation single defect of 1 mm was created on bearing SKF BB1 B420205 by electrical discharge machining. The frequency spectrum of the signal captured from the bearing housing has been plotted in Fig. 6. These are amplitudes of regular train. For the comparison of the frequency spectra of the single defect and two defects, a second defect was created on outer race at the angular difference of 30° and frequency magnitudes were measured. The spectra for single defect at 0° and two defects at 0° & 30° are overlapped as seen in Fig. 6. In Fig. 6 the same frequency components can be noticed in both cases (i.e. single defect and two defects), with different magnitudes due to phase differences. No additional frequencies have been observed due to time delay between two defects.

The experiments have been repeated for the single and two defects (defects width 0.5 mm) on the inner race of the bearing SKF BB1 B420205. Figure 6 shows the frequency spectrum of single defect. The second defect was created at the angular difference of 30° from the first defect. The vibrations have been caputerd for two defects and their frequency spectrum is also plotted in Fig. 6 (a & b), which is overlapped on spectrum of single defect. The comparison of two spectra shows that there is no additional frequency present in case of two defects. Small variation in overlapping frequencies (X-axis) is observed due to difficulty in maintaining exactly same shaft rotational speed in both cases.

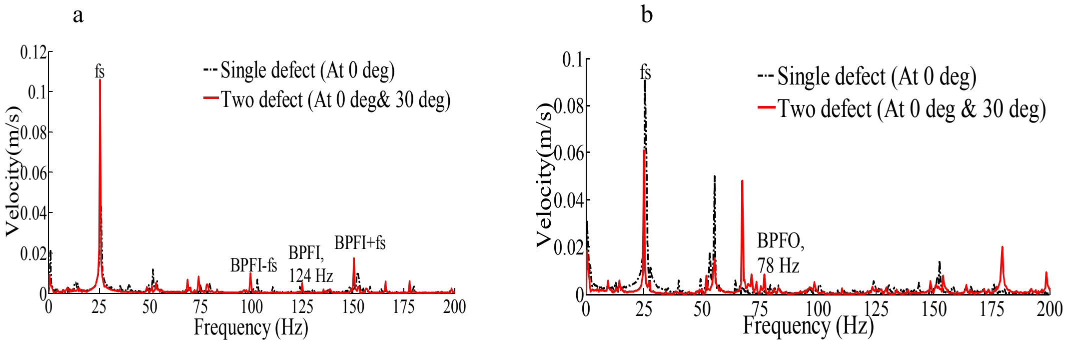

Fig. 6 Experimental vibration spectrum of bearing having single defect and two defects on (a) Inner race (b) Outer race (N_s =1500 rpm)

5. Conclusions

Vibrations generated in deep groove ball bearings due to the presence of multiple defects on their races have been studied in time and frequency domains. Time delay between two successive impulses due to multiple defects has been noticed in time domain analysis. The information related to defect angle and number of defects is

clearly observed in time domain analysis. However, when the defect angle is the same as the angle between two successive balls, the vibration response of bearing having two defects is the same as the vibration response of bearing having single defect. It is essential to mention here that the information related to the number of defects and the time delay between successive impulses could not be seen in the frequency domain analysis. The frequency spectra of single defect and two defects are found to be identical i.e. no additional frequencies are noticed due to impulses generated with time delay between two defects. However, the magnitudes of frequencies are varying based on the angles between two defects due to change in phase angles. The authors believe that this in-depth theoretical and experimental vibration studies provide better understanding of vibrations due to multiple defects on bearing races for practising engineers and researchers.

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